Proceedings of the 7th International Conference on Asian and Pacific Coasts
(APAC 2013) Bali, Indonesia, September 24-26, 2013

SEDIMENT TRANSPORT AROUND PORT DEVELOPMENT AREA IN ESTUARY

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ABSTRACT: This study focuses on sediment transport and tidal exchange dynamics in the Scheldt estuary at Kruibeke (about 5 km upstream of the Antwerp Harbour, Belgium) in the late 1990s and early 2000s. The involved parameters are tidal cycle measurements of total suspended sediment concentrations and fluxes, tidal water elevation, flow velocities, river discharges and tidal discharges. The data show that the net tidal water discharge over a full tidal cycle ranges between 96 and 729 $m^3 s^{-1}$ for the period 1995-1998, and between 67 and 319 $m^3 s^{-1}$ for the period 2002-2005. In the vicinity of Kruibeke, though the measured depth-integrated flood flow velocity is over 10% stronger than that of the ebb current, the net mass transport is ebb oriented. The depth-integrated suspended sediment concentration reaches up to 829 g m^{-3} and 394 g m^{-3} for the periods 1995-1998 and 2002-2005 respectively. Sediment load was clearly higher for 1995-1998 than that of for 2002-2005. The sediment mass load versus tidal water discharge reveals a correlation with appreciated R^2 values of 0.9 and 0.8 for the periods 1995-1998 and 2002-2005 respectively. Evaluation of the temporal relation between sediment mass load and tidal water volume for a tidal phase, ebb and flood respectively, shows some correlation. Comparison of freshwater discharge and estuary net sediment discharge reveals a net export of sediments out of the estuary in the vicinity of Kruibeke. Yet, this net transport of sediments has notably decreased in the course of time from 1995 to 2005. Quantification and computation of resuspension of bed sediments scoured by tidal currents and further dispersed and enhanced by particle de-flocculation and flocculation and resulted particle settling could help to understand sediment transport dynamics in the Scheldt estuary.

Keywords: Water discharge; hydraulic dynamics; sediment transport; estuary.

INTRODUCTION

The morphology of the Scheldt Estuary (Belgium, the Netherlands) is shaped by natural processes and anthropogenic interference such as maintenance dredging of shipping channel and harbors since 1960s. The site of investigation Kruibeke is located about 5 km upstream of the Antwerp Harbor, Belgium. This area is the only straight channel part existed in the Scheldt estuary and is situated right in the estuarine turbidity maximum (ETM) zone (Fig. 1). The ETM zone is one of the most dynamic and complicated hydrological systems of the Scheldt estuary. Despite the various research programs associated with the ETM zone, there is still great scarcity of data and information on the physical processes controlling the sediment transport. Long-term field data is therefore crucial for the development of numerical models for sediment transport and sustainable management strategies.

The sediment load is a key parameter in determining hydraulic dynamics and boundary conditions in numerical models. As a first step towards addressing scarcity of information on the sediment transport in the ETM zone of the Scheldt estuary, the aim of this study is to interpret and describe several crucial parameters that are essential for the calibration and implementation of numerical models for sediment transport and balance in the Scheldt estuary for the periods 1995-1998 and 2002-2005. In particular the study intends to obtain information on: (1) the temporal relation between sediment flux and flow velocity; (2) the relation between sediment flux and tidal phase; and (3) the relation between global sediment load and fresh water discharge.

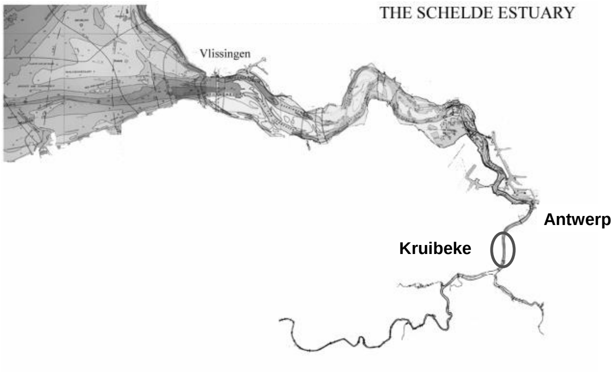

Fig. 1. Location of the investigation site in the Scheldt estuary.

In the periods of 1995-1998 and 2002-2005 a range of tidal cycle measurements were carried out on the Scheldt at Kruibeke, where water depth, flow velocity and suspended sediment concentration (SSC) were

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measured at several depths along the water column. Data were processed to produce quantification of flow velocity, tidal water discharge, sediment flux and sediment load. The results give an important appreciation for the monitoring of sediment transport in the Scheldt and support for future numerical modeling of the sediment balance.

DATA COLLECTION AND PROCESSING

Field data were collected from complete tidal cycle measurements carried out during two periods 1995-1998 and 2002-2005 at high and low river discharge in the vicinity of Kruibeke about 5 km upstream of the Antwerp Harbor, Belgium.

Water depth, salinity, conductivity, flow velocity and suspended sediment concentration (SSC) are the primary parameters measured in the field investigations.

The depth-integrated flow velocity is determined by

$$\bar{v} = \frac{1}{h}\int_{\alpha}^{h} v\,dz \tag{1}$$

where $\bar{v}$ is the depth-integrated flow velocity (m s^{-1}); v is the flow velocity at a given depth (m s^{-1}); a is the small reference elevation above the bed or bottom; h is the water depth (m) at the measuring point; and z is the elevation (m) above the bottom at the measuring point.

The depth-integrated water flux q_w (m^2 s^{-1}), above the bed layer $z > a$, is calculated as

$$q_w = \int_{\alpha}^{h} v\,dz \tag{2}$$

The corresponding total water discharge Q_w (m^3 s^{-1}) is obtained from integration of the water discharge over the entire width w (m) of the channel. The total water discharge is time dependent with varying water depth over a tidal cycle. Consequently, the total water volume V_w (m^3) defines the amount of water passing a cross section over a given period of time.

The sediment flux q_s (g m^{-1} s^{-1}) above the bed layer $z > a$ is obtained from the depth-integrated advective flux of sediment Cv above the bed layer $z > a$,

$$q_s = \int_{a}^{h} C\,v\,dz \tag{3}$$

where C is the measured SSC (g m^{-3}). The corresponding total suspended sediment discharge Q_s (g s^{-1}) is obtained from integration of the sediment flux q_s over the entire width w (m) of the channel. The suspended load L_s (g) defines the amount of sediment Q_s in suspension passing a cross section over a given period of time.

It is known that water flow and suspended sediment concentration are rarely uniformed over a river cross section. Owing to the restrained settings of the given field measurement program, the data analysis in this study applied the assumption that water and suspended sediment discharge are constant over the cross section of the measuring site. However the data can be attuned if the variation is known over the cross section at the measuring site. Nevertheless the results provide an important insight of the sediment transport at Kruibeke for support of the numerical modeling of the sediment balance.

SEDIMENT DISCHARGE AND TIDAL WATER DISCHARGE

The temporal relation between sediment discharge and tidal water discharge is illustrated in Fig. 2.

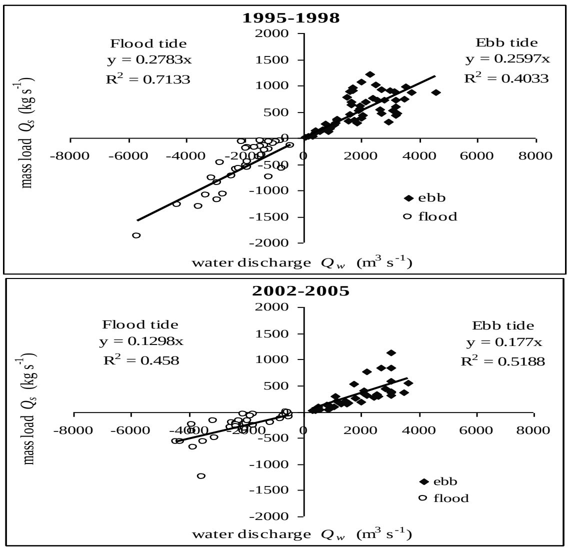

Fig. 2. The temporal relation between suspended sediment discharge and tidal water discharge over the entire width of the channel over a tidal phase.

The sediment discharge Q_s, expressed as kg s^{-1}, reflects the total suspended sediment discharge over the entire width of the channel. The tidal water discharge Q_w, expressed as m^3 s^{-1}, is the total water discharge over the entire width of the channel.

The data show that the net tidal water discharge range between 96 and 729 m^3 s^{-1} for the period 1995-1998, and between 67 and 319 m^3 s^{-1} for the period 2002-2005. In the vicinity of Kruibeke, in this ETM zone, the depth-integrated SSC reaches up to 829 g m^{-3} and 394 g m^{-3} for the periods 1995-1998 and 2002-2005 respectively. The average sediment discharge ranges 544 – 855 kg s^{-1} for ebb and 523 – 977 kg s^{-1} for flood during 1995-1998, and 328 – 589 kg s^{-1} and 288 –

538 kg s^{-1} for ebb and flood respectively for the period 2002-2005. The maximum tidal water discharge for ebb and flood are respectively 4553 m^3 s^{-1} and 5710 m^3 s^{-1} for 1995-1998, and 3639 m^3 s^{-1} and 4419 m^3 s^{-1} for 2002-2005. In the vicinity of Kruibeke, the depth-integrated flood flow velocity is overall over 10% stronger than that of the ebb current, while the mass transport is either in equilibrium or slightly ebb dominant. The data do not indicate flood oriented transport.

Fig. 2 shows the temporal relationship between sediment discharge (Q_s) and tidal water discharge (Q_w) for ebb and flood during the two different periods. It is clear from Fig.2 that a notable larger amount of sediment load is found for the period 1995-1998 than the period 2002-2005. The sediment discharge versus tidal water discharge demonstrates a reasonable correlation. Quasi-equilibrium ebb and flood sediment discharge is found for the period 1995-1998, while a clear ebb dominated sediment discharge is found for the period 2002-2005 (Fig. 2). This observed difference in sediment discharge might be contributed by a number of factors such as the amount of resuspended bottom sediment swept away into the water column by the tidal current, and the amount of sediment supply from the river basin (Chen *et al*. 2005; Chen *et al*. 2007a). Hence, computation of the critical bottom shear stress and quantification of the amount of resuspended bottom sediment could help to explain the observed difference in sediment discharge.

For the period 1995-1998, the relationship between discharge (Q_s) and water discharge (Q_w) is

$$Q_s = 0.2597\ Q_w$$

with a R^2 value of 0.4 for ebb, and

$$Q_s = 0.2783\ Q_w$$

with a R^2 value of 0.7 for flood. The difference between ebb and flood is very small, and rather insignificant. If one relationship for a complete tide is assumed the equation becomes

$$Q_s = 0.2674\ Q_w$$

with a R^2 value of 0.9 for a complete tidal cycle.

For the period 2002-2005, the relationship between discharge (Q_s) and water discharge (Q_w) is given by

$$Q_s = 0.177\ Q_w$$

with a R^2 value of 0.5 for ebb, and

$$Q_s = 0.1298\ Q_w$$

with a R^2 value of 0.4 for flood. The difference between ebb and flood is larger, but not really very different. If one relationship for a complete tide is assumed the equation becomes

$$Q_s = 0.1508\ Q_w$$

with a R^2 value of 0.8 for a complete tidal cycle.

Comparing the linear regressions, there is 44% more sediments transport in the period 1995-1998 than in the period 2002-2005. This implies that sediment transport reduced considerably in the period 2002-2005. It is evident that the difference between the period 1995-1998 and the period 2002-2005 is remarkable and thus suggests a profound change in sediment transport.

SEDIMENT MASS LOAD AND TIDAL PHASES

To assess the total water flow and sediment mass transport for ebb and flood requires a full tidal cycle measurement. However this is not always the case owing to practical difficulties and the rigidity of the field program. For the period 1995-1998, the tidal cycle measurements missed the last hour. This gives difficulty in calculation. In view of, to certain extent, the periodic nature of a tidal cycle, the values from the first measurement are used in the calculation also as the values for the last missing measurement.

The temporal relation between sediment mass load and tidal water volume for ebb and flood is shown in the Fig.3 for all the measurements during the period 1995-2005. The sediment mass load L_s (kg) reflects the amount of sediment in suspension passing a cross section over either an ebb or a flood tidal phase, and the tidal water volume V_w (m^3) is the amount of water passing a cross section over either an ebb or a flood tidal phase.

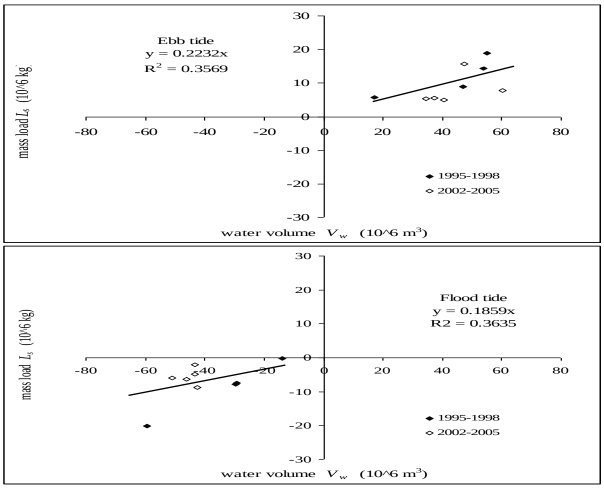

Fig. 3. The temporal relation between sediment mass load and tidal water volume passing a cross section over a tidal phase.

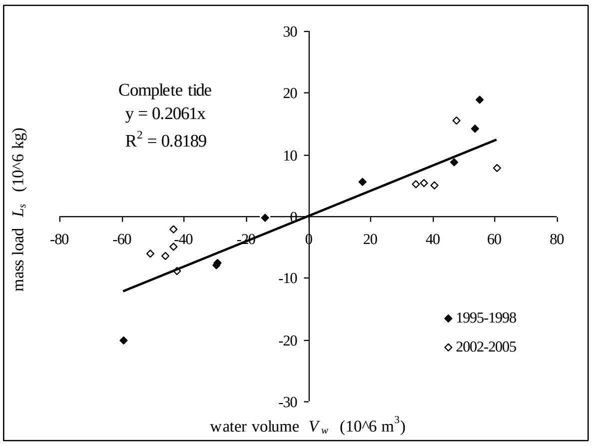

Fig. 4. The temporal relation between sediment mass load and tidal water volume passing a cross section over a complete tidal cycle.

The sediment mass load (L_s) versus tidal water volume (V_w) shows some correlation. Comparing the results between Fig.2 and Fig.3, the linear regressions give the similar equations. There seems to be a small ebb dominated sediment mass load exists at Kruibeke. It can also be observed that the sediment mass load varies much less with the tidal water volume in 2002-2005 than in 1995-1998. With a similar tidal water volume a much higher amount of sediments is transported in 1995-1998 than in 2002-2005, and such difference is quite pronounced during the flood phases of those two periods.

During the ebb phase, the relationship between sediment mass load (L_s) and tidal water volume (V_w) is

$$L_s = 0.2232\, V_w$$

with a R^2 value of 0.36.

During the flood phase, the relationship between sediment mass load (L_s) and tidal water volume (V_w) is given by

$$L_s = 0.1859\, V_w$$

with a R^2 value of 0.36. The difference between ebb and flood is not that great.

If all data is combined the relationship becomes

$$L_s = 0.2061\, V_w$$

with a R^2 value of 0.8 (Fig. 4).

NET SEDIMENT LOAD AND FRESH WATER DISCHARGE

The temporal relation between the net sediment mass load and the fresh water discharge is analyzed. Data of fresh water discharge is received from E. Taverniers, Flemish government, Department of Mobility and Public Works, Maritieme Schelde. The freshwater discharge values fit well within the documented range of the Scheldt river discharge varying from 50 m^3 s^{-1} during dry summer to 300 m^3 s^{-1} during wet winter months with an annual average between 100 m^3 s^{-1} and 200 m^3 s^{-1} (e.g., Chen et al., 2005; Taverniers, 2000).

The net sediment mass load Q_{sn}, expressed as kg s^{-1}, is the algebraic difference between ebb and flood sediment mass load L_s (kg) divided by a time span of a full tidal cycle (ca. 12.5 hours), or in other words, it is the net sediment mass transport passing a cross section at any given moment over a complete tidal cycle. The values of net sediment mass load (Q_{sn}) shall be interpreted with caution, as these are calculated as the difference of two quite large values, i.e., the ebb and flood sediment mass loads, each of which is quantified with a large degree of uncertainty.

Nevertheless, overall an obvious ebb dominant sediment transport exists in the Scheldt estuary at Kruibeke. It is clear that the net sediment mass load increases with freshwater discharge, and the relation between the net sediment mass load (Q_{sn}) and the fresh water discharge (Q_{fw}), though weak, is found:

$$Q_{sn} = 1.0503\, Q_{fw}$$

for the period 1995-1998, and

$$Q_{sn} = 0.7224\, Q_{fw}$$

for the period 2002-2005.

The linear relation between net sediment load and fresh water discharge, based on the available data sets, does not yield a strong correlation for the periods 1995-1998 or 2002-2005 due to the large uncertainty as explained above. There are also occasional events of flood slightly prevailed transport of the sediments. This implies that, in a tidal driven estuary, sediment load is not necessarily to be a function of the freshwater discharge. The generation of the temporal sediment movement direction is a complex multi-mechanism system (c.f., Chen *et al*., 2007b; Wartel *et al*., 2007). Apart from the freshwater discharge, it is partly ascribed to the resuspension of the fine channel bed sediments by relative strong and dominant flood tidal currents and further enhanced by fine sediment flocculation that could cause an increase of high SSC and keep most of the sediments in suspension momentarily in a tidal phase (c.f., Chen *et al*., 2005; Chen *et al*., 2007b). The differences in current velocities result in differences in tidal discharges that could generate a net import of sediments towards upstream. Nevertheless, by and large, comparison of the river freshwater discharge and estuary net sediment discharge reveals a net export of sediments out of the estuary in the vicinity of Kruibeke. This net transport of sediments has notably decreased from 1995-1998 to 2002-2005 as discussed earlier. Hence, all the results clearly indicate a decrease of sediment transport in the course of time from 1995 to 2005.

CONCLUSIONS

The evaluation and interpretation of the long-term (1995-2005) field data has yielded some essential information on the dynamics of sediment transport and balance in the Scheldt estuary at Kruibeke.

The sediment mass load versus tidal water discharge demonstrates a reasonable correlation. A notable larger amount of sediment load is found for the period 1995-1998 than the period 2002-2005. Quasi-equilibrium ebb and flood sediment mass load is found for the period 1995-1998, while a clear ebb dominated sediment mass load is found for the period 2002-2005. The remarkable difference between these two periods suggests a profound change in sediment transport dynamics.

Assessment of the temporal relation between sediment mass load and tidal water volume for a tidal phase, ebb and flood respectively, shows close correlation. Sediment mass load varies much less with the tidal water volume in 2002-2005 than in 1995-1998. With a similar tidal water volume a much higher amount of sediments is transported in 1995-1998 than in 2002-2005, and such difference is quite pronounced during the flood phases of the two periods.

Comparison of the river freshwater discharge and estuary net sediment discharge reveals a net export of sediments out of the estuary in the vicinity of Kruibeke. A simple linear relation between sediment load and fresh water discharge, based on the available data sets, does not yield a strong correlation probably because of the large uncertainty in the determination of the net sediment transport, as large quantities of sediments are moving up and down the same sector during a tidal cycle.

The results imply, in a tidal driven estuary, that sediment transport is a complex multi-mechanism processes. In fact, in the Scheldt estuary, it may be emanated from zones, which reflect fundamentally different sediment-transport regimes with respect to time and spatial sequences, with primarily depositional phase, erosional phase and resuspension phase. Quantification and computation of resuspension of bed sediments scoured by tidal currents and further dispersed and enhanced by particle de-flocculation and flocculation and resulted particle settling could help to understand sediment transport dynamics in the Scheldt estuary.

ACKNOWLEDGEMENTS

The research vessel “BELGICA” was put at authors’ disposal by the Management Unit of the North Sea Mathematical Models (MUMM). The authors thank the captains and crews of the research vessels “BELGICA” and “VEREMANS” for their help during cruises on the Scheldt Estuary.

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